HIGHLIGHTS OF THE KLOE EXPERIMENT AT DAΦNE

The KLOE Collaboration [a]

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The KLOE experiment at DAΦNE has collected ~ 450 pb^{-1} of e^+e^- collisions at center of mass energy $W \sim 1.02$ GeV. Preliminary results are presented for the most recent measurements: limit on the BR($K_S \to 3\pi^0$), BR of the K_{e3} decay of the K_S and determination of the hadronic cross section.

1 Introduction

DAΦNE, the Frascati ϕ factory, is an e^+e^- collider working at $W \sim m_\phi \sim 1.02$ GeV with a design luminosity of $5 \cdot 10^{32}$ cm^{-2} s^{-1}. ϕ mesons are produced, essentially at rest, with a visible cross section of ~ 3.2 μb and decay into K^+K^- (K_SK_L) pairs with BR of $\sim 49\%$ ($\sim 34\%$). These pairs are produced in a pure $J^{PC} = 1^{--}$ quantum state, so that observation of a K_S (K^+) in an event signals (tags) the presence of a K_L (K^-) and viceversa; highly pure and nearly monochromatic K_S, K_L, K^+ and K^- beams can be obtained. Neutral kaons get a

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momentum of $\sim$ 110 MeV/c which translates in a slow speed, $\beta_K \sim 0.22$. K_S and K_L can therefore be distinguished by their mean decay lengths: $\lambda_S \sim 0.6$ cm and $\lambda_L \sim 340$ cm.

The KLOE detector consists essentially of a drift chamber, DCH, surrounded by an electromagnetic calorimeter, EMC. The DCH [1] is a cylinder of 4 m diameter and 3.3 m in length which constitutes a large fiducial volume for K_L decays (1/2 of λ_L). The momentum resolution for tracks at large polar angle is $\sigma_p/p \leq 0.4\%$. The EMC is a lead-scintillating fiber calorimeter [2] consisting of a barrel and two endcaps which cover 98% of the solid angle. The energy resolution is $\sigma_E/E \sim 5.7\%/\sqrt{\mathrm{E(GeV)}}$. The intrinsic time resolution is $\sigma_T = 54$ ps$/\sqrt{\mathrm{E(GeV)}} \oplus 50$ ps. A superconducting coil surrounding the barrel provides a 0.52 T magnetic field.

During 2002 data taking, the maximum luminosity reached by DAΦNE was $7.5 \cdot 10^{31}$ cm^{-2} s^{-1}. Although this is lower than the design value, the performance of the machine was improving during the years and, at the end of 2002, we collected ~ 4.5 pb^{-1}/day. The whole sample (2001-2002) amounts to 450 pb^{-1}, equivalent to 1.4 billion ϕ decays. Recently, the machine has been upgraded and KLOE is resuming its data taking in spring 2004.

2 Kaon physics

The tagging of K_L and K_S is the basis of each KLOE analysis for neutral kaons. Similar techniques have been developed also for charged kaons. The selection of $K_S \to \pi^+\pi^-$ decays provides an efficient tag for K_L decays. K_S's are instead tagged by identifying a K_L interaction, K_L-crash, in the calorimeter, which has a very distinctive signature given by a late ($\beta_K = 0.2$) high-energy cluster not associated to any track. In either case, reconstruction of one kaon establishes the trajectory of the other one with an angular resolution of 1° and a momentum resolution of $\sim$ 2 MeV. Several analyses [3,4] have been already completed or are under completion at KLOE. We discuss only the two most advanced items in progress.

2.1 Direct search of $K_S \to 3\pi^0$

The decay $K_S \to 3\pi^0$ is a pure CP violating process. The related CP violation parameter η_{000} is defined as the ratio of K_S to K_L decay amplitudes: $\eta_{000} = A(K_S \to 3\pi^0)/A(K_L \to 3\pi^0) = \varepsilon + \varepsilon'_{000}$ where ε describes the CP violation in the mixing matrix and ε'_{000} is a direct CP violating term. In the Standard Model we expect η_{000} to be similar to η_{00}. The expected branching ratio of this decay is therefore $\sim 2 \cdot 10^{-9}$, making its direct observation really challenging. The best upper limit on the BR (i.e. on $|\eta_{000}|^2$) has been set to $1.5 \cdot 10^{-5}$ by SND [5] where, similar to KLOE, it is possible to tag a K_S beam. The other existing technique is to detect the interference term between $K_S K_L$ in the same final state which is proportional to η_{000}. The weighted average of the best published values [6,7] gives: $\eta_{000} = (0.08 \pm 0.11) + i \cdot (0.07 \pm 0.16)$. Apart from the interest in observing this decay directly, the large uncertainty on η_{000} limits the precision on CPT invariance test via the unitarity relation [8]. In the most general way, a neutral kaon state [9] is expressed as: $K_{S,L} = K_{1,2} + (\varepsilon \pm \delta)K_{2,1}$ where K_1 and K_2 are the two CP eigenstates and δ is a CPT violation parameter. The unitarity relation in this base can be written as:

$$(1 + i\tan(\phi_{sw}))(\Re(\varepsilon) - i\Im(\delta)) = \sum (A^*(K_S \to f)A(K_L \to f)/\Gamma_S) \tag{1}$$

where the sum runs over all the possible decay channels f, and $\tan(\phi_{sw}) = 2\Delta m_{S,L}/(\Gamma_S - \Gamma_L)$. According to ref. [10], the value of $\Im(\delta) = (2.4 \pm 5.0) \cdot 10^{-5}$ is limited by the measurement on η_{000}. Neglecting this term, the same analysis yields $\Im(\delta) = (-0.5 \pm 2.0) \cdot 10^{-5}$.

Our selection starts by requiring a K_L-crash tag and six neutral clusters coming from the interaction point, IP. A tight constraint on β and moderate requirements on energy and angular acceptance are applied in order to have a large control sample for the background, while retaining large selection efficiency for the signal. On 450 pb^{-1} we have an initial sample of 39 k events

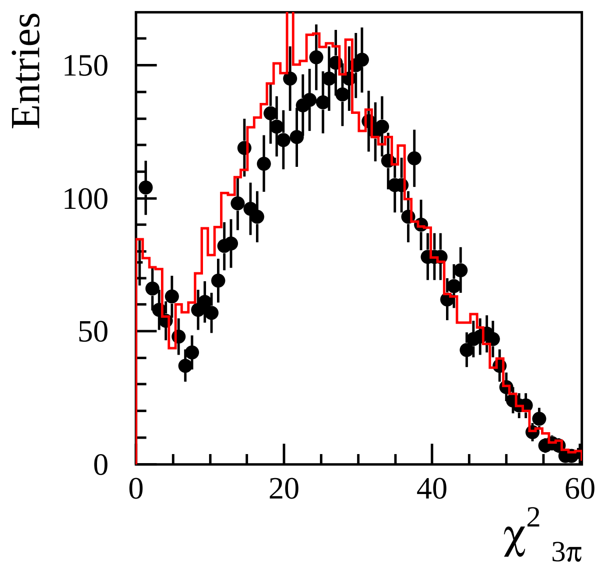

Figure 1: Distribution of $\chi^2_{3\pi}$ when $14 < \chi^2_{2\pi} < 40$: (left) total sample after acceptance selection, (right) all analysis cuts applied; black dots (solid line) are data (MonteCarlo).

dominated by $K_S \to 2\pi^0$+ 2 fake γ. To reduce the sample, a kinematic fit which imposes K_S mass, K_L 4-momentum conservation and $\beta = 1$ for each γ is applied. Only the events with $\chi^2_{\rm fit}/{\rm ndf} < 3$ are retained for further analysis. However, this cut improves the rejection power only of a factor ~ 3 and, to better discriminate $2\pi^0$ *vs* $3\pi^0$ final state, we build two pseudo-χ^2 variables: $\chi^2_{3\pi}$, which is based on the 3 best π^0 mass estimates and $\chi^2_{2\pi}$, which selects 4 out of the 6 photons providing the best kinematic agreement with the considered decay.

The distribution of $\chi^2_{3\pi}$ is shown in Fig. 1.a for the whole preselected sample by requiring $\chi^2_{2\pi}$ to be in a high acceptance region for the signal. The presence of the large peak, at low $\chi^2_{3\pi}$ values, indicates another source of contamination related to the production of fake K_L-crash followed by a $K_L \to 3\pi^0$ decay. These fake, late clusters are produced by the pions from $K_S \to \pi^+\pi^-$ interacting on the quadrupoles. Our MonteCarlo, MC, reproduces well this background source (3% of the total rate). To reduce it to a negligible amount we veto events with tracks coming from the IP. A signal box region in the $\chi^2_{2\pi}$ *vs* $\chi^2_{3\pi}$ plane has been defined by optimizing the upper limit in the MC sample. With an efficiency $\varepsilon_{3\pi} = (22.6 \pm 0.8)\%$, we count 4 events for an expected background $N_b = 3 \pm 1.4 \pm 0.2$. Folding the proper background uncertainty, we quote the number of $K_S \to 3\pi^0$ decay to be below 5.8 at 90% C.L. In the same tagged sample, we count $3.8 \cdot 10^7$ $K_S \to 2\pi^0$ events used for normalization. We finally derive ${\rm BR}(K_S \to 3\pi^0) \leq 2.1 \cdot 10^{-7}$ at 90% C.L. which improves of a factor ~ 100 the previous measurement. This result can also be translated into a limit $|\eta_{000}| < 0.024$ at 90% C.L. which makes the contribution of the uncertainty for this decay negligible in the calculation of $\Im(\delta)$.

2.2 Semileptonic decays and V_{us}

The semileptonic charge asymmetries for $K_{S,L}$ are related to the CP, CPT violation parameters ε, δ as [9,11] : $A_{S,L} = \frac{\Gamma_s(\pi^+e^-\overline{\nu}) - \Gamma_s(\pi^-e^+\nu)}{\Gamma_s(\pi^+e^-\overline{\nu}) + \Gamma_s(\pi^-e^+\nu)} = 2\Re(\varepsilon) \pm 2\Re(\delta)$. A non zero value of $A_S - A_L$ would signal CPT violation either in the K_S-K_L mixing or in direct transitions violating the $\Delta S = \Delta Q$ rule. While A_L is measured with high precision [12] a measurement of A_S is still not existent. KLOE has already measured [13] the BR for the K_{e3} decay of the K_S using 17 pb^{-1} collected in 2000. A new measurement with the collected statistics of 450 pb^{-1} gives a first determination of A_S. Moreover, a precise determination of $\Gamma_s(\pi e \nu)$ permits us to evaluate V_{us}.

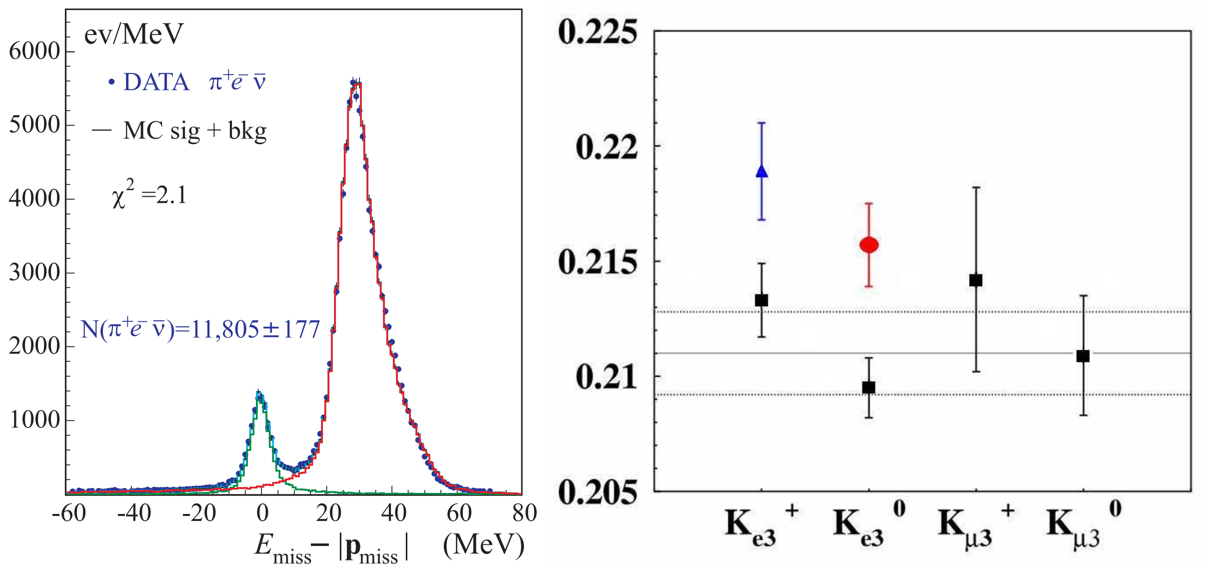

Figure 2: (Left) $E_{\rm miss} - |P_{\rm miss}|$ distribution after time-of-flight cuts for the $\pi^+e^-\overline{\nu}$ sample: dots are data, solid lines are MonteCarlo expectations. (Right) evaluations of $|V_{us}f_+^{K^0\pi^-}(0)|$ from PDG 2002 numbers (squares), BNL-E865 (triangle), KLOE preliminar number from K_{e3} of the K_S (circle).

The $K_S \to \pi e\nu$ decays are selected, after K_L-crash tagging, by the presence of two oppositely charged tracks from a vertex close to the IP. Loose momentum and angular cuts, and the requirement of an upper cut on $M(\pi^+\pi^-)$, reject most of the $K_S \to \pi^+\pi^-$ background. The π and e assignments are made using time-of-flight so that the BR's to final states of each lepton charge can be measured independently. In Fig. 2.a, the $E_{\rm miss} - |P_{\rm miss}|$ distribution, obtained by using the K_S momentum estimated from the K_L-tag, shows a pronounced peak around zero due to the neutrino. The number of signal events is obtained from a fit which uses the MC distributions for signal and background with their normalizations as free parameters. The generator used for the signal properly handles the final state emitted radiation through an infrared finite treatment. By normalizing to the number of $K_S \to \pi^+\pi^-$ events counted in the same tagged sample, we get the following preliminary values for BR$(K_S \to \pi^+e^-\overline{\nu}) = (3.54 \pm 0.05 \pm 0.04) \cdot 10^{-4}$ and BR$(K_S \to \pi^-e^+\nu) = (3.54 \pm 0.05 \pm 0.04) \cdot 10^{-4}$. Without considering the charge, we get BR$(K_S \to \pi e\nu) = (7.09 \pm 0.07 \pm 0.08) \cdot 10^{-4}$, which is consistent with our old measurement, improving of a factor 5 the statistical error. On the basis of these results, we derive also the first measurement ever done of the charge asymmetry for the K_S: $A_S = (-2 \pm 9 \pm 6) \cdot 10^{-3}$. This value is consistent with the much more precise A_L evaluations. With the 2 fb^{-1} expected from next running we could perform a consistency test of A_S with $2\Re(\varepsilon)$. We need instead at least 20 fb^{-1} to determine δ with a precision comparable to the one obtained by CPLEAR.

The determinations of $|V_{us}|$ and $|V_{ud}|$ provide the most precise test of CKM unitarity: $(|V_{ud}|^2 + |V_{us}|^2 = 1 - \Delta)$. In PDG 2002 [14], $\Delta = 0.0042 \pm 0.0019$ shows a $2.2\,\sigma$ deviation from unitarity. In this test, $|V_{us}|$ account for 0.0011 of the error and is derived from the measurement of partial widths [15] in K_{l3} decays:

$$\Gamma(K_{l3}) \propto |V_{us}f_+^{K^0\pi^-}(0)|^2 I(\lambda_+, \lambda_0, 0)(1 + \delta_{SU2} + \delta_k) \tag{2}$$

where $f_+^{K^0\pi^-}(0)$ is the kaon form factor a $t = (P_k - P_\pi)^2 = 0$, $\lambda_{+,0}$ are the form factor slopes, I is the integral of the phase space and δ_{SU2}, δ_k are the isospin-breaking and electromagnetic radiative corrections; these corrections are of the order of $\sim 1{\div}2\%$. By measuring the BR(K_{l3}) in a photon inclusive way and correcting for the lifetimes the product $|V_{us}|f_+^{K^0\pi^-}(0)$ can be derived.

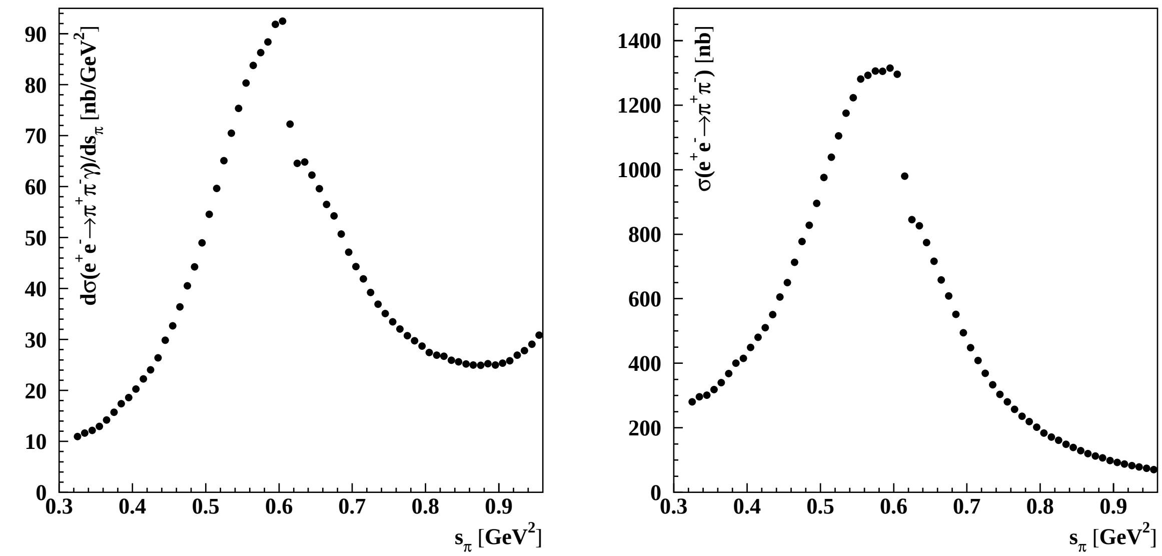

Figure 3: (Left) preliminary KLOE measurement of $d\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma)/ds_\pi$ for 140 pb^{-1} of 2001 data; the cross section is inclusive in θ_π and with $\sin\theta_\gamma < \sin 15^o$; (Right) "bare" cross section for $e^+e^- \rightarrow \pi^+\pi^-$.

The four evaluations of this quantity from published data are in good agreement as shown in Fig. 2.b. On the other hands, the recent measurement of BNL-E865 [16] gives a discrepant value which is instead consistent with unitarity and the current determination of $|V_{ud}|$. Our preliminary measurement of the BR($K_S \rightarrow \pi e \nu$) allows us to obtain a new value of $|V_{us}| f_+^{K^0\pi^-}(0)$ in much better agreement with E865 and unitarity (see Fig. 2.b). The discrepancy between the K_S and K_L, $K^\pm$ determination of V_{us} calls for new measurements. In the longer term, KLOE should be able to determine all four K_{l3} BR's to much better than 1% and significantly improve the determinations of the lifetimes as well as the form factors slopes.

3 Hadronic physics

Other than producing kaons, the ϕ meson decays $\sim 15\%$ of the time in $\rho\pi$ and through radiative decays is a good source of pseudoscalar (η, η') and scalar (f_0, a_0) mesons. Although a lot of interesting analyses have been published [17,19,20,21] on these items, and their findings are being improved with the larger statistical sample available, we do not discuss them here.

The recent updated measurement of the anomalous magnetic moment of the muon, a_μ, by the E821 collaboration [22] has instead led to renewed interest in accurate measurement of the hadronic cross section. From the theoretical side, the hadronic contributions on a_μ, a_μ^{had}, cannot be evaluated in perturbative QCD but via a dispersion relation which integrates the hadronic cross section multiplied by an appropriate kernel. The process $e^+e^- \rightarrow \pi^+\pi^-$ below 1 GeV accounts for $\sim$ 70% to the a_μ^{had} value and of its error. The most recent measurement of $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ by CMD-2 [23], done with energy-scan of e^+e^- collisions, claim statistical (systematic) precision of 0.7% (0.6%) and imply a difference of $-2.7\,\sigma$ of the calculated value of a_μ with respect to the E821 measurement. Moreover, it gives also a rather strong disagreement with the value of a_μ^{had} obtained using τ-data [24] after isospin correction.

KLOE is determining in an original way this cross section as a function of s_π, the squared center of mass energy of the $\pi\pi$ system, in the region $0.3 < s_\pi < 1$ GeV^2. DAΦNE operates at fixed energy $W \sim m_\phi$, but Initial State Radiation (ISR) lowers the available beam energy

for the di-pion system. We measure the cross section for the process $e^+e^- \rightarrow \pi^+\pi^-\gamma$ and use the PHOKHARA generator [25] to relate $\sigma(\pi^+\pi^-\gamma)$ with $\sigma(\pi^+\pi^-)$. Complications from processes with final-state radiation are avoided by restricting the selection to events with small-angle photons ($\theta_\gamma < 15^o$) where ISR events completely dominate the sample. The γ's are not detected, but s_π and θ_γ are instead reconstructed by using DCH information on the π's. A description of the analysis strategy used can be found elsewhere [26]. The preliminary KLOE data shown in Figs. 3 provide an independent measurement (also from the systematic point of view) of this cross-section from CMD-2 data. We calculate the dispersion integral in the same region used by CMD-2 ($0.37 < s_\pi < 0.93$ GeV^2) to get: $a_\mu^{had} = (376.5 \pm 0.8 \pm 5.9) \cdot 10^{-10}$. This results is in good agreement with the CMD-2 number: $a_\mu^{had} = (378.6 \pm 2.8 \pm 2.3) \cdot 10^{-10}$ confirming the discrepancy of e^+e^- data with τ-data and with the measured value of a_μ.

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